

Infrasound Observations of Variability During Stratospheric Warmings¹

DAVID H. RIND AND WILLIAM L. DONN

Lamont-Doherty Geological Observatory of Columbia University, Palisades, N.Y. 10964

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ABSTRACT

Observations of natural infrasound produce a continual record of the sound velocity, a function of wind and temperature, at the reflection level in the upper atmosphere. Under normal conditions in winter the reflection level, for sound generated by ocean waves to the east of Palisades, N. Y., is in the lower thermosphere. During the circulation changes associated with stratospheric warmings, winds near the stratopause may become east or north, allowing infrasound to be reflected from this level. We are then provided with a continuous record of sound velocity near the stratopause. The methods which are used to distinguish between stratospheric and thermospheric sound reflection are discussed, and circulation changes for each year are cataloged.

During the warming event sound velocities in the stratosphere are shown to vary radically, with fluctuations of up to 60 m s^{-1} in a few hours time period. These short time period variations, observable only because of the continuous nature of infrasound recording, are greater than expected and indeed constitute a significant fraction of the total wind and temperature variation associated with the event at our latitude. As such they imply significant energy variations on shorter time scales than those usually considered important in stratospheric dynamics. Some possible explanations for these observations are given.

1. Introduction

It is commonly observed that during stratospheric warmings the energetics of the stratosphere are dominated by wavenumbers 1 and 2 (e.g., Perry, 1967). Depending upon the horizontal velocity of these waves the time scale of wind and temperature changes at any particular location can vary markedly, but the variations should be consistent with the large scale pattern of wave influence. Smaller length-scale influences should be minimized due to the inability of these scale waves to propagate vertically in the presence of the normal background west winds, and numerous observational studies have indeed found only small energy associated with wavenumbers higher than 3 or 4. However, quite small-scale energy would not be observable with the widely separated observational network of meteorological rockets, and a large slant range combined with large-scale data smoothing prevent satellite temperature observations from indicating such variations. Small-scale time variations are also not usually observable due to the time delay between normal observations. Thus, if significant energy and associated wind and temperature variations exist at small time and space scales it would most likely be difficult to detect by regular means.

During the circulation changes associated with stratospheric warmings, infrasound generated to our

east by ocean waves is reflected near the stratopause, and its trace velocity observed across a tripartite array is equal to the sound velocity, a function of both wind and temperature, at the reflecting level (Rind *et al.*, 1973). Because infrasound generation and recording are continuous, we are provided with a continuous record of the stratopause sound velocity during warmings. At such times we commonly observe large variations of sound velocity on short time scales, ranging from a few hours to a few days. These variations are a significant fraction of the total sound velocity variation of the entire (warming) event in our vicinity, and as such seem to indicate important energy variations on a shorter time scale than might otherwise be expected. We will discuss here the technique involved, and observations during several events, and also suggest possible causes for these observations.

2. Infrasound technique

a. Initial identification of stratospheric reflection

Natural infrasound of 5 s period has been recorded for the past ten years at Palisades, N. Y., with a tripartite array of sensors. Under normal winter conditions infrasound generated to our east by sea waves in the Atlantic Ocean is reflected from the lower thermosphere at which height tidal wind variations induce diurnal and semidiurnal amplitude variations in the signal observed at the surface (Donn and Rind, 1972; Rind and Donn, 1975). Fig. 1a shows the typical

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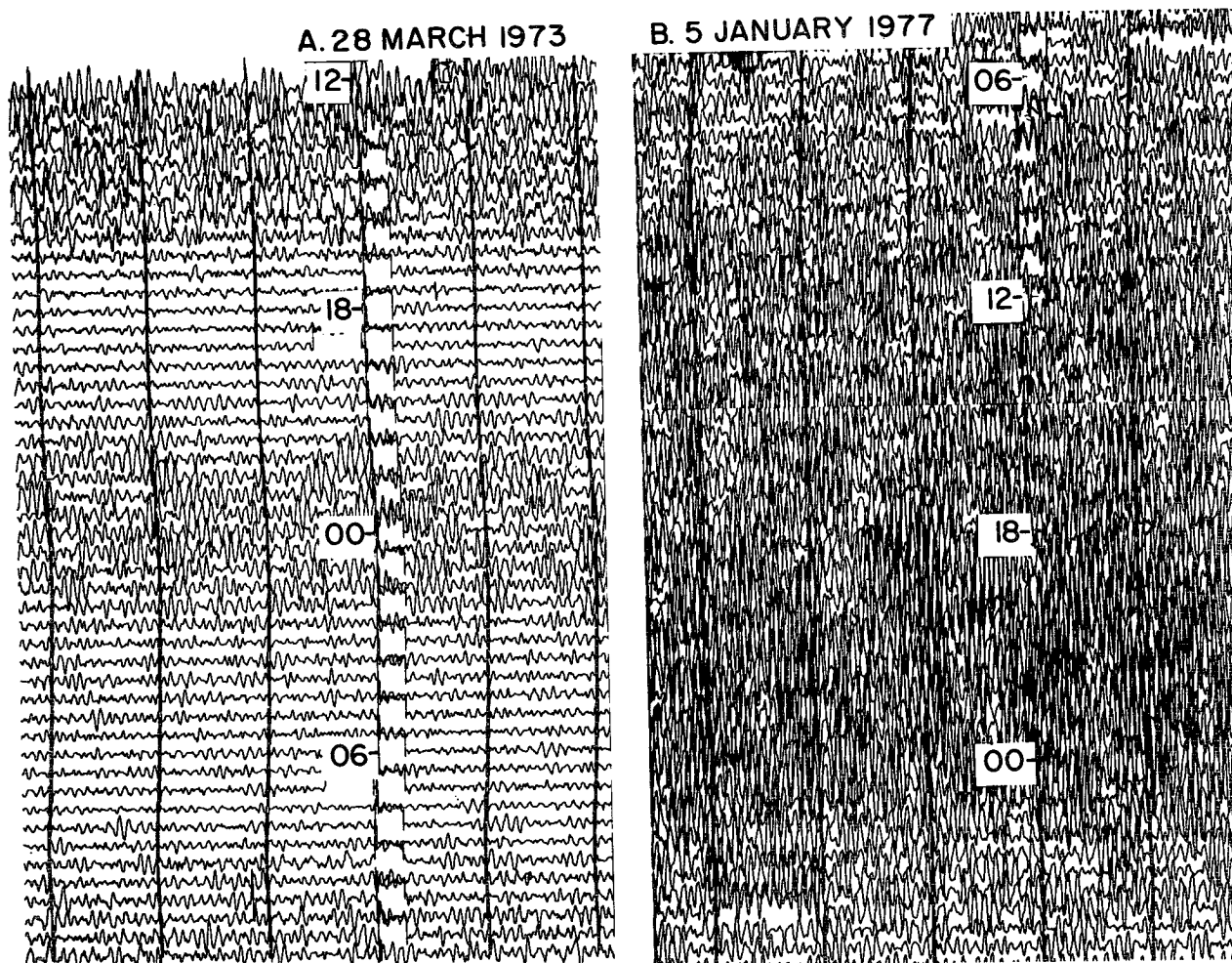


FIG. 1. Infrasonograms at Palisades, N.Y. Each is a portion of a 24 h drum recording on which a few minutes of each 30 min line are shown giving a full-day presentation. All times are EST. Time marks on the lines are at intervals of one minute. Larger time breaks appear each hour with major breaks at 0700 and 1900. Fig. 1a, which is the record for 28–29 March 1973, shows the typical semi-diurnal amplitude variations due to tidal wind effects in the lower thermosphere. Fig. 1b, for 5 January 1977, displays the high amplitudes throughout the day indicative of reflection from the stratosphere during a warming.

semidiurnal amplitude variation associated with the tidal effect in the lower thermosphere. (All times are EST.) Infrasound is recorded on rotating seismic type drums which allow amplitude variations with time to be easily discernible.

During stratospheric warmings, when the normally strong stratospheric westerlies weaken or reverse, signal from the east or northeast is reflected from the stratosphere. Such signal has continuously high amplitudes compared to normal winter signal without both the dominant tidal amplitude variations and the dissipation incurred from thermospheric reflection (Donn and Rind, 1972).

Fig. 1b shows a typical example of an all-day high amplitude infrasound pattern observed during the circulation change associated with the stratospheric warming of January 1977. The appearance of the record

in 1b compared to that of 1a is the immediate indicator of a circulation change in the stratosphere.

In order for signal to be reflected from the stratosphere the sound velocity, which is a function of both wind and temperature, must exceed the surface sound velocity. Fig. 2 gives the resulting sound velocity from the east based on wind and temperature observations at Wallops Island, during normal conditions (curve A) as well as during times of continuously high infrasound amplitude at Palisades, indicative of stratospheric reflection (curves B through G). The sound velocity in these latter cases in the stratosphere exceeds that at the surface thus allowing for stratospheric reflection. Thus, the first indication of the onset of a stratospheric circulation change during winter in our region is the alteration in appearance of the visual records. Analysis of such records shows the effect of the circulation changes in a quantitative way. The amplitude variation

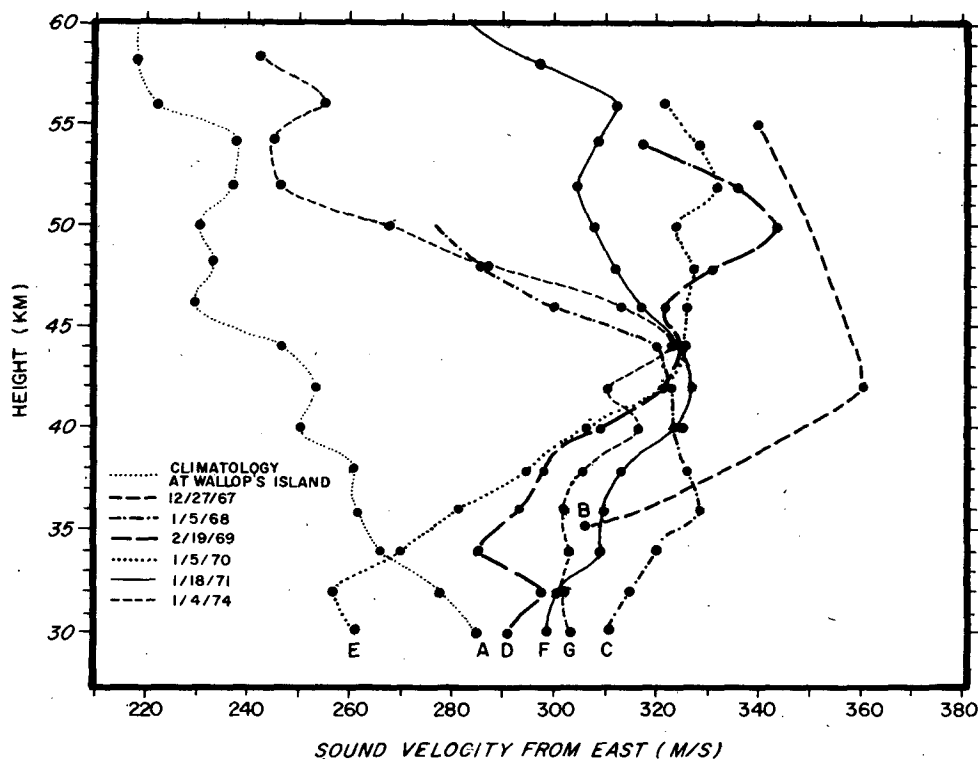


FIG. 2. Sound velocity profiles for signal from the east at Wallops Island for climatological averages (1961-76) (curve A), and for different dates for which infrasound observations suggested stratospheric reflection (B-G).

due to tidal wind influences during normal winter thermospheric reflection is much reduced when reflection occurs in the stratosphere. This effect is shown clearly in Table 1, which compares the ratio of the amplitude range to mean amplitude for times of normal thermospheric reflection and reflection from lower levels during events in the years listed. Due to the thermal wind condition it is necessary for the temperature gradient to reverse before the stratospheric circulation in our vicinity can reverse; hence these

TABLE 1. Ratio of amplitude range to mean amplitude for 12 h periods during intervals of stratospheric and thermospheric reflection.

	Stratospheric reflection	Thermospheric reflection
1967-68	0.24 ± 0.11	0.75 ± 0.23
1969	0.25 ± 0.15	0.74 ± 0.20
1969-1970	0.35 ± 0.14	0.81 ± 0.28
1971	0.30 ± 0.12	0.72 ± 0.16
1973	0.25 ± 0.10	0.72 ± 0.27
1973-74	0.27 ± 0.14	0.77 ± 0.31
1974-75	0.19 ± 0.05	0.85 ± 0.21
1975-76	0.29 ± 0.14	0.69 ± 0.15
1976-77	0.30 ± 0.23	0.76 ± 0.23
Average	0.28 ± 0.15	0.77 ± 0.24
	128 h	102 h

circulation changes are always associated with stratospheric warmings.

b. I/M ratios

As an independent indication that the height of infrasound reflection has decreased from the thermosphere to the stratosphere we compare the infrasound amplitude with the amplitudes of microseisms which are seismic waves of the same period generated simultaneously by ocean waves. Microseisms provide independent indicators of source strength and are obviously unaffected by temporal variations in atmospheric propagation characteristics. This comparison guarantees that unexpectedly high infrasound amplitudes are not simply the result of increased source strength. We form the ratio (I/M) between the infrasound and microseism amplitudes as originally described in Rind and Donn (1975). Both are received at Lamont, infrasound on a tripartite array of capacitor microphones and microseisms on a three component seismograph. The comparison is made only for those cases in which the sources were the same. This is established by comparing the azimuth of approach and the frequency for the two signals as described by Donn and Naini (1973). For infrasound from the east this occurs about two-thirds of the time (Rind, 1976). Infrasound that is reflected from the stratosphere in

winter will undergo less dissipation than that reflected from the thermosphere; hence for the same source conditions, as determined by microseism amplitudes, there will be a higher I/M ratio. However, the effect of the source location must in some way be considered because the amplitude of M varies strongly with crustal conditions along different propagation paths (although for a given path, the amplitude of M is not time dependent as is I). Thus the I/M value must be interpreted as a function of microseism strength which largely removes the effect of source location.

In order to determine the reflection level of infrasound using I/M we must know the ratio for specific reflection heights. We have shown that in winter thermospheric reflection is responsible for the signal we normally observe at the surface, and that the reflection level varies between about 105 and 115 km. The heights are estimated from atmospheric time-dependent models based on actual observations of wind and temperature (Rind and Donn, 1975; Rind, 1976). The I/M ratio was determined for reflection at these heights from some 300 h of winter data between 1968 and 1977; the results are shown in Table 2 and Fig. 3. The ratios vary somewhat from case to case (due to various source locations, sound velocity variation and uncertain calibration) as indicated by the standard deviations, but the means are significantly different for reflection at 115 and for 105 km. The lower ratios for signal reflected from 115 km are due to the increasing dissipation found between 105–115 km (Donn and Rind, 1972; Rind, 1977). For signal reflected from above 115 km the ratio should be lower than the bottom curve in Fig. 3; for signal reflected from between 105 and 115 km the ratio should fall between the two curves, and for signal reflected below the thermosphere the ratio should be above the value indicated by the 105 km curve.

TABLE 2. I/M values for infrasound reflection under different winter conditions.

	Microseism amplitude (μ m)				
	0.5–1	1–1.5	1.5–2	2–2.5	2.5–3
105 km	3.99(1.99)	3.18(0.93)	2.73(0.56)	2.30(0.51)	1.94(0.62)
115 km	1.75(0.59)	1.58(0.89)	1.28(0.43)	0.97(0.32)	0.78(0.30)
Warming	4.22(0.61)	4.85(1.33)	3.86(1.23)	2.76(0.64)	2.19(0.29)
Unlisted					
warming	7.25(1.51)	8.08	3.20(0.75)	2.93(0.50)	2.68(0.25)
	Microseism amplitude (μ m)				
	3–3.5	3.5–4	4–4.5	4.5–5	>5
105 km	1.80(0.55)	1.46(0.53)	1.34(0.52)	1.46(0.43)	0.74(0.29)
115 km	0.76(0.21)	0.75(0.36)	0.56(0.10)	0.50(0.29)	0.35(0.15)
Warming	1.40(0.05)	2.06(0.39)	1.45(0.24)	2.35(0.27)	1.15(0.28)
Unlisted					
warming	2.50(0.60)	2.32(0.60)	1.17(0.26)		

Data samples: 300 hours for 105 and 115 km reflection, 150 hours for warmings, 50 hours for unlisted warmings.

Parenthetical values give standard deviations.

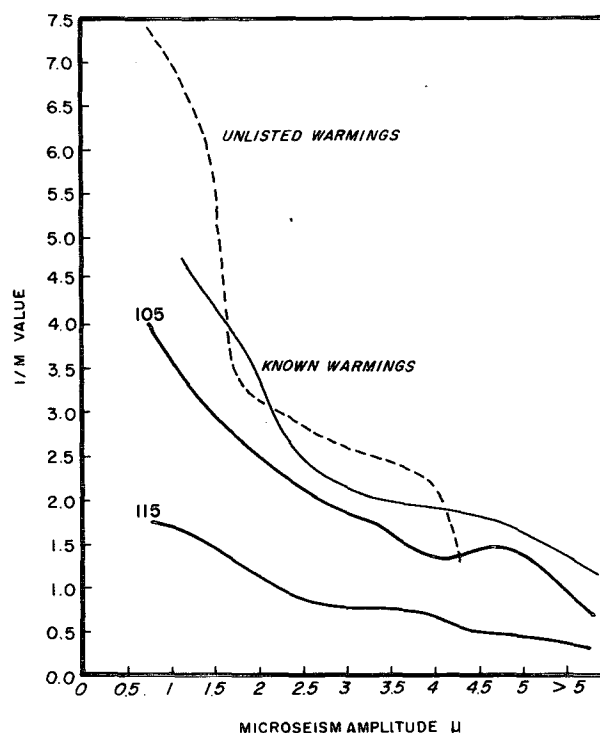


FIG. 3. Infrasound-microseism ratios (I/M) as a function of microseism amplitude for reflection of infrasound from upper atmospheric levels under conditions with and without stratospheric warmings. The numbers on two curves refer to reflection heights in the lower thermosphere. The curves showing both known and unlisted warmings are for stratospheric reflections.

c. I/M values and stratospheric circulation charges

The I/M value was calculated for all cases with continuously high amplitude during the day, suggestive of stratospheric reflection as noted earlier. These cases were then divided into those which corresponded to known warmings and possible warmings on the basis of rocket observations (and their absence) from Wallops Island, 3° to our south. The sound velocity from the east was determined throughout the stratosphere for days around those when infrasound was continuously high. A "warming" was an event when the sound structure in the stratosphere was capable of reflecting infrasound from the east. Rocket observations were often made on only one day of several of which infrasound observations suggested stratospheric warmings; these adjacent days were also included in the "known" warming category. Dates of "possible" warmings were days when no supporting rocket data were available at times of high infrasound amplitude.

I/M ratios for the known warmings are given in the third row of Table 2 and in Fig. 3. The relatively high I/M values for each of the microseism amplitude ranges indicate that reflection occurred below 105 km. As reflection should be coming from the stratosphere under these conditions, this amounts to a verification

TABLE 3. List of warmings (circulation changes) observed with infrasound at Palisades, N. Y.

1967	December: 23-28
1968	January: 5-6; 17-18*; 20
1969	February: 20-21; December: 31
1970	January: 1-5*; 7*-8*
1971	January: 17-19
1972	November: (17-18)**
1973	January: 8-10; 13-14; 21; 30; February: (4-5)**
†1974	January: 4*; February: 9*-10*; 18*-19*; 24-25; 26*-28*; March: 11-12
1975	January: 5-6
1976	January: 1; 8*-10*; 12*-13*; December: 26-27; 29-31
†1977	January: 4*-5; 8*; 13*-14*; 15-15; March: (9-10)*

† No records: 20 February 1974, 1-2 January 1977 and 10-12 January 1977.

* Marginal warmings: reduced I/M values and increased tidal influence indicative of only weak reflection in the stratosphere.

** Circulation change above the stratosphere: increased tidal influence although high I/M values, with no possibility of stratospheric reflection from Wallops Island data.

of the application of the I/M ratio and the use of microseisms to allow for source strength. The ratio for stratospheric reflection averages 1.33 times higher than the ratio for 105 km reflection and this factor matches that calculated from the greater dissipation with thermospheric reflection (Rind, 1977).

The ratios for the possible warmings are also shown

in Table 2 row 4 and Fig. 3. They are also significantly higher than the 105 km reflection values; this implies that reflection at these times also occurred below thermospheric levels. Thus, previously unknown circulation changes were identified by infrasound observations. Table 3 gives a list of the changes in our area detected by our analysis of infrasound from 1967 to 1977. Most of these correspond to times when warmings were observed by Wallops Island rocketsondes on at least one of the days; also included are events which have not been detected previously. Several of the events apparently took place above the stratosphere, as they show some thermospheric tidal influence and Wallops Island disallows any stratospheric reflection.

Fig. 4 shows the time history of infrasound trace amplitudes (top curve) and normalized I/M values (lower curve) from 18 December to 3 January 1968. The horizontal line at the 1.0 ratio level is the value for reflection at 105 km. Values below this line indicate reflection above 105 km; those above the line indicate reflection at lower levels. From 18-23 December the low amplitudes showing tidal oscillations indicate thermospheric reflection. The I/M values also indicate thermospheric reflection. Increased amplitudes from 23 through 28 December suggest a stratospheric circulation change as supported by the high I/M values, which indicates that the increased infrasound strength

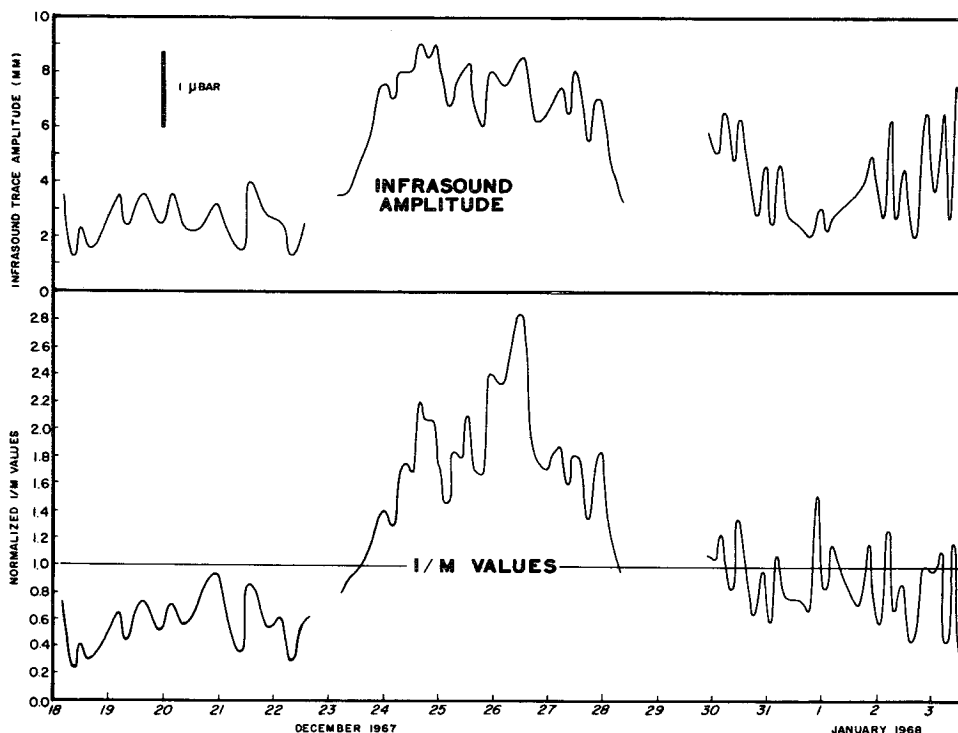


FIG. 4. Time histories of infrasound amplitude (upper curve) and normalized I/M values (lower curve) for 18 December 1967 through 3 January 1968. The normalization is accomplished by dividing by the appropriate 105 km I/M value and thus the horizontal line at I/M value of 1.0 (± 0.2) represents mean values for reflection at 105 km. Breaks in the curves are times of high wind obscuration of signal.

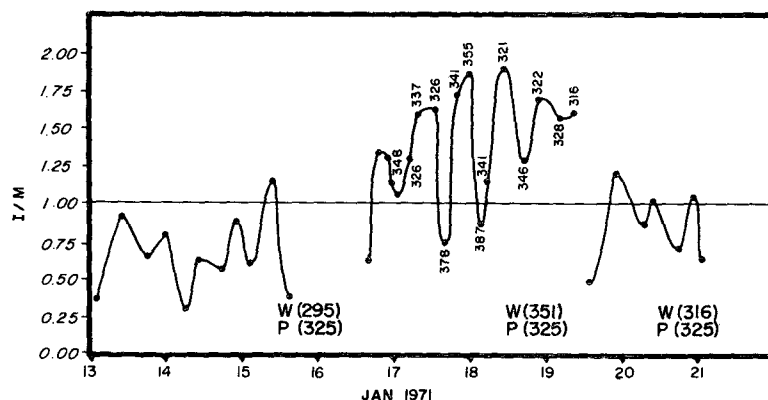


FIG. 5. Normalized I/M values for 13–21 January 1971. The value of 1.0 again represents 105 km reflection with stratospheric reflection indicated by values continually above this line. Also shown are the Wallops Island peak stratospheric sound velocity (W) for signal from the observed eastern azimuth, the surface sound velocity at Palisades (P), and the recorded infrasound trace velocities (near the curve).

is not the result of increased source activity. The I/M peak, which is a function of the strength of the sound channel, suggests that the peak of the effect occurred during 26 December. Intervals of high infrasound amplitudes from 30 December through 3 January do not indicate renewed stratospheric reflection because the I/M ratios returned to thermospheric reflection values. Hence, the high amplitudes indicate source strength increases. These results are typical of the majority of the warming cases we examined.

3. Sound velocity variations during stratospheric warmings

As noted earlier, the trace velocity recorded across the array equals the sound velocity at the reflection level. Having determined that stratospheric reflection occurred at certain times in winter we then determined further how the sound velocity, a function of both wind and temperature, varied during these times. In general, there were large variations in short periods of time which are not explicable by current theories. Several of these cases will be described below.

Fig. 5 shows the I/M ratios (normalized) for 13–21 January 1971. Reflection below the lower thermosphere (when the I/M ratio exceeded 1) occurred during the period between 1800 January 16 and 1200 January 19, except for several periods during the latter part of 17 January and early on 18 January. The recorded trace velocities varied between 320 and 360 m s^{-1} , except during the times of thermospheric reflection when they rose to higher values representative of the thermospheric sound velocities. Wallops Island data, compared with Palisades surface level sound velocities, indicated that stratospheric reflection did take place during the time interval involved, but not before or after. Only during the time of high I/M values did the sound velocity in the stratosphere exceed the ground level value. The

sound velocity measured at Wallops Island (351 m s^{-1}) during the event is in good agreement with the sound velocity computed for the stratopause region from the recorded trace velocity.

Fig. 6 depicts the sound velocity variation of the recorded signal (lower curve) for the recorded azimuths (upper curve) during the time of stratospheric reflection. Fluctuations of 20–40 m s^{-1} occur in a period of a few hours. If this is simply the effect of wind changes, then wind variations of the same order of magnitude are occurring with these short time scales. If this is the result of temperature effects, it would require temperature variations of around 60 K in a few hours. A combination of the two effects is perhaps likely. The effect is not due to varying azimuth of the source which changes slowly and generally independent of the sound velocity variations. The azimuth change was caused by a northward drift of the source.

Another example of the variability during a warming is presented in Fig. 7. The bottom curve shows the I/M ratios from 4 January through 6 January 1975, and establishes the existence of stratospheric reflection beginning about 2200 on 4 January and lasting uninterruptedly until 1400 on 6 January. The middle curve indicates that strong signal sound velocity variations occurred during the event which was associated with a major stratospheric warming. Variations of up to 60 m s^{-1} were recorded in two hours, with again little azimuth change (top curve). These observations are at a location (41°N) which is further south than those most affected by warming events, and yet impressive variations within a few hours are still recorded. Observations during other warming events also indicate variations of these magnitudes.

The degree of variation during these warmings can be appreciated by comparing them with the sound velocity over a comparable period of time during

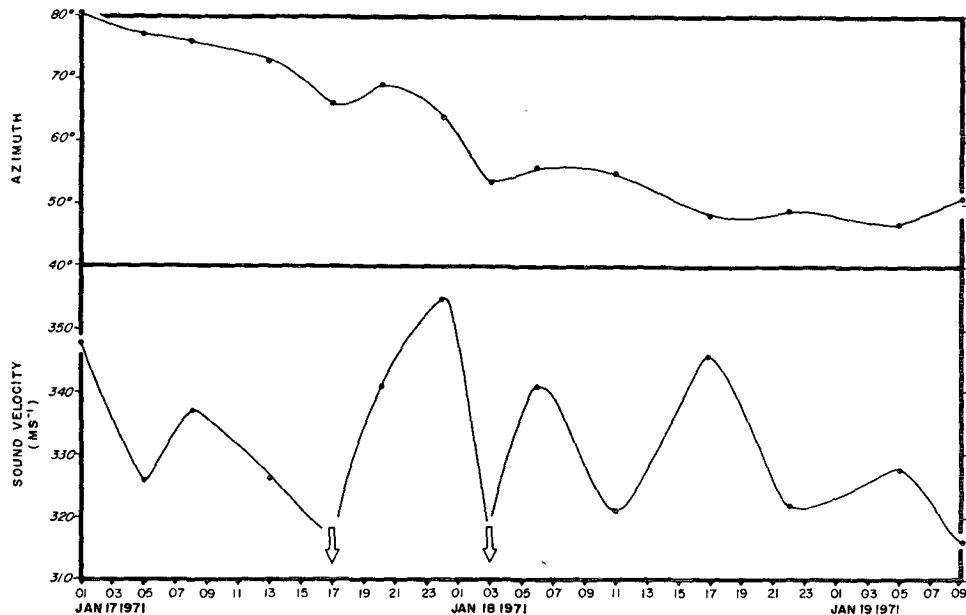


FIG. 6. Infrasound trace velocity (lower curve) and azimuth (upper curve) variations during 17–19 January 1971. Arrows indicate times when the stratospheric sound velocity decreased below the surface sound velocity and infrasound reflection came from the thermosphere.

summer, when reflection of infrasound normally occurs in the stratosphere due to the prevailing east winds. Fig. 8, for the period of 6 August 1970 to 9 August 1970, indicates quite small signal sound velocity variations indicative of the steady east winds during this season.

The small variations that are present about 1400 and midnight local time are related to the diurnal tide in the stratosphere, which tends to peak from south and north respectively at these times. The sound velocity variations per hour during the warmings are 12 times

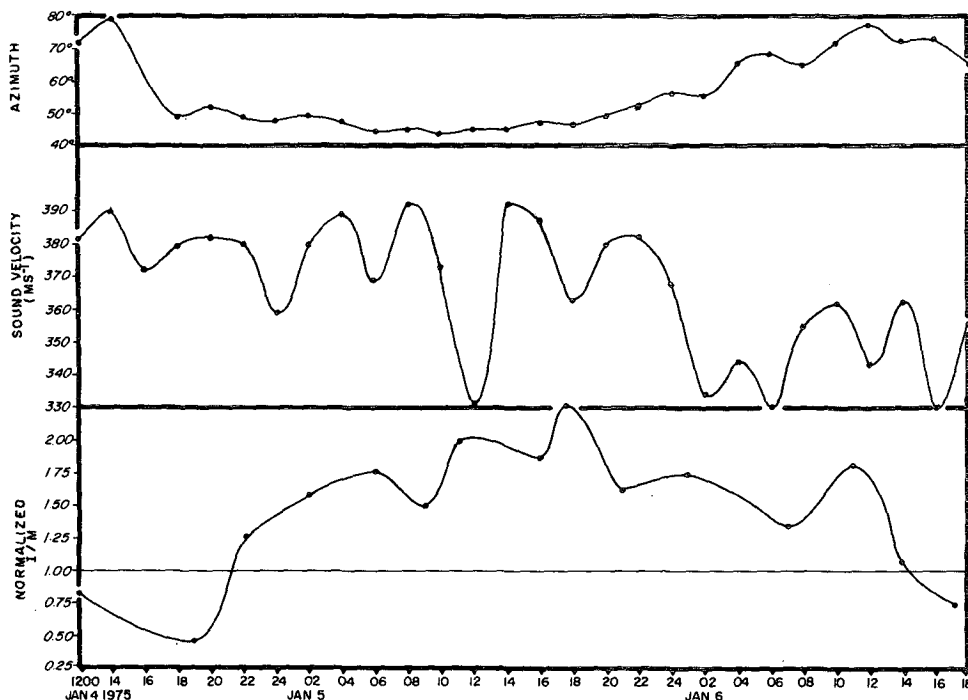


FIG. 7. Normalized I/M values, infrasound trace velocity and azimuth for 4–6 January 1975. Presentation the same as for Fig. 4 and 6.

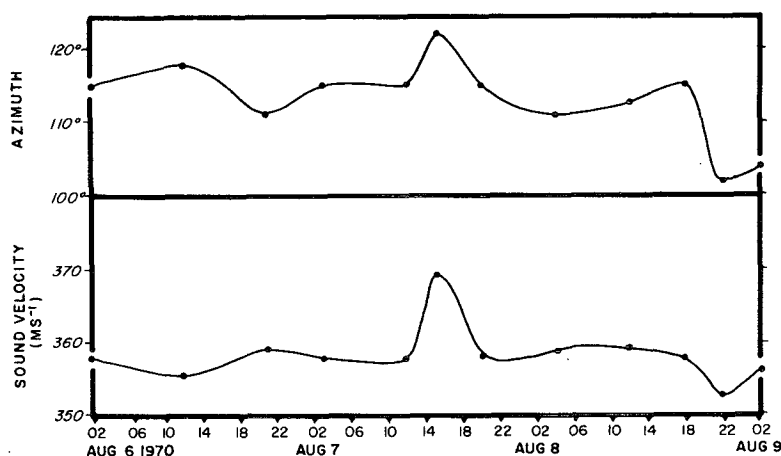


FIG. 8. As in Fig. 6 except for 6–9 August 1970.

that recorded during the relatively steady east wind regime in summer.

4. Discussion

What effects are responsible for such strong variations within short time intervals? The infrasound technique cannot specify the level in the stratosphere from which reflection is taking place, so it is conceivable that different sound velocities are associated with differing reflection levels. This does not explain the phenomena, for the changed reflection level itself indicates that strong variations are occurring rapidly. The signal strength during these events is quite high, and the resulting uncertainty in the sound velocities obtained is at most on the order of 5 m s^{-1} . Also, as noted, the source direction is not undergoing rapid variations, so source location variations are not responsible. This leaves variations in wind and temperatures as the cause of observed velocity variations.

If these effects are associated with fluctuations in the large-scale waves themselves, they then represent a rapid pulsing in the energy of the planetary waves propagating from the troposphere. While such variations cannot be ruled out, there have been no observed variations of large magnitude with time periods on the order of a few hours associated with the large scale waves. Observations are not well-suited to evaluate this effect. Gravity-wave wind fluctuations of a few hours period are well known, although in general of smaller magnitude, with an rms magnitude of 10 m s^{-1} at 65 km (Justus and Woodrum, 1973). Traveling planetary waves also provide at most this magnitude wind variation (Deland, 1970; Justus and Woodrum, 1973) although with a much larger period. The possibility of small-scale baroclinic or barotropically unstable waves, moving rapidly, cannot be dismissed as, once again, observational techniques are not well-

suited to observe them. With records at only one location we are in no position to comment upon the length scale of these fluctuations or their coherence over any distance, both of which would help distinguish among the suggested causes. Whatever the reason, the variations in sound velocity produced are a significant percentage of the total sound velocity change during a stratospheric warming, and the associated energy which appears to be available on short time scales should not be overlooked.

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